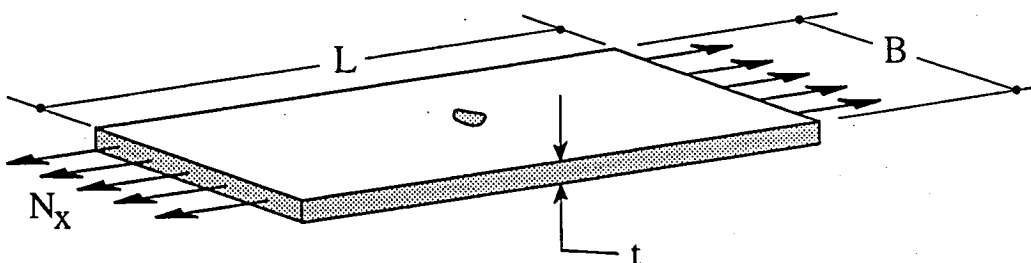


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A NEW MERIT FUNCTION FOR EVALUATING THE FLAW TOLERANCE OF COMPOSITE LAMINATES



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by

Martin M. Mikulas, Jr. and Rod Sumpter

ABSTRACT

Advanced composite materials are providing notable weight savings in numerous aerospace and non-aerospace applications by virtue of their uniquely high strength-to-density ratio and high stiffness-to-density-ratio. However, their full potential for high performance has yet to be achieved because of the low tolerance of the "brittle" material to impact, holes, flaws, and localized discontinuities due to relatively low toughness. In the present paper a new and simple merit function is proposed for maximizing the strength performance of flawed composite laminates for different design requirements. This new merit function takes into account the flaw tolerance of a composite laminate as well as its stiffness. After development of the new merit function, an example is presented of its application to a practical laminate family.

INTRODUCTION

Advanced composite materials are providing notable weight savings in numerous aerospace and non-aerospace applications by virtue of their high strength-to-density ratio and high stiffness-to-density-ratio. However, their full potential for high performance has yet to be achieved because of the low tolerance of the "brittle" material to impact, holes, flaws, and localized discontinuities. Numerous studies have been conducted over the past fifteen

years to develop new failure theories and to experimentally characterize the flaw performance of composite materials. An important observation made in these studies was that flawed graphite/epoxy laminates tend to fail at strain levels around 0.004¹. In other words, even though an unflawed laminate may be able to sustain strain levels greater than 0.01, the same laminate with even slight flaws could fail at strain levels on the order of 0.004. Because of this observation, composite structures are presently designed such that their ultimate strain levels do not exceed this lower level associated with a flaw.

The primary mechanisms contributing to this low ultimate strain level are low resin toughness and high local stresses due to stress concentrations. Over the past ten years, the materials community has been exploring ways of improving resin toughness and this work is leading to improvements in flawed-laminate ultimate strain capacity. The second area, associated with high stress concentrations, also offers a potential for improving the flaw tolerance of composite materials because of the large number of design variables available in the laminate. However, a major obstacle to exploring laminates with lower stress concentrations is the lack of an appropriate merit function for consistent evaluation of laminate performance.

The design of a laminate for a specific application typically involves a delicate balance between material strength and structural stiffness. For example, a high-aspect-ratio aircraft wing will require specified levels of axial and torsional stiffness while maintaining a high level of strength, which may be distinct from that required for a low-aspect-ratio wing. On the other hand, the need for torsional stiffness may not be as high for a launch vehicle. For most orbital space structures the primary need is axial stiffness with lower requirements for torsional stiffness and strength. Thus, depending upon the application, the laminate requirements will be different.

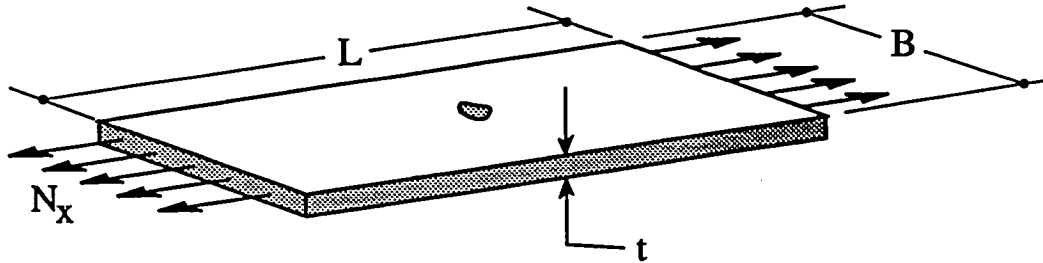
In the present paper a new and simple merit function is proposed for assessing the strength performance of flawed composite laminates for different design requirements. This new merit function takes into account the flaw tolerance of a composite laminate as well as its stiffness. A demonstration of the new merit function is presented for the flaw case of a large circular hole. Since this is only one condition that may be critical for a strength-designed laminate, other potential failure modes must be considered. For example, the critical design requirement could be associated with a crack, a small hole, a local flaw, or impact damage. In order to

determine whether improved laminates can be obtained for these conditions, the designs would have to be evaluated with an approach similar to that used for the large hole in the present paper. For these other failure modes, either a point stress failure criterion or a fracture mechanics approach would have to be used for evaluation. After development of the new merit function, examples are presented of its application to graphite/epoxy laminates.

MERIT FUNCTION DERIVATION

Composite laminates are unique in that they are made up of constituent lamina that can provide a wide spectrum of effective material properties. Consider, for example, the in-plane properties of an orthotropic laminate family made up of a $(0_m, \pm\theta_n, 90_p)$ set of lamina. By changing the percentage of each of the three sets of lamina, and by changing the angle θ , the four independent global orthotropic elastic constants, E_x , E_y , G_{xy} , and ν_{xy} , can be changed over a large range. However, for specific applications there exist specifications on the relative stiffnesses that highly constrain the design freedom available. Another requirement of extreme importance in the design of a laminate is its capacity to carry load in the presence of a flaw. The term flaw herein is used to denote any deviation from a perfect plate such as a hole, a crack, or impact damage.

It is well recognized that the flaw tolerance of a laminate can change considerably depending upon its effective in-plane orthotropic stiffness properties. For example, the stress concentration factor for a circular hole is quite low in a $\pm 45^\circ$ laminate (~ 2) but is quite high in a unidirectional laminate (~ 6). A corresponding fact for these laminates is that the extensional stiffness E_x for the $\pm 45^\circ$ laminate is very low, while that for the unidirectional laminate is very high. Between these extreme cases there exist many laminates, each of which has different values of the stress concentration factor k and in-plane stiffnesses. A logical question that remains to be answered is, which is best from a flaw tolerance aspect? Although low extensional stiffness laminates tend to have lower stress concentration factors, they carry less load by virtue of their lower stiffness. Thus, there could be an optimum laminate which carries the most load in the presence of a flaw. In this section a merit function is developed to enable quantification of the flaw tolerance of the wide range of laminate lay-ups available.



Sketch a.- Flawed composite plate.

A schematic of the flawed composite laminate to be studied is shown in Sketch a. For this laminate the weight is written as:

$$W = \rho BtL \quad (1.1)$$

where ρ is the weight density of the material, and B , t , and L , are the width, thickness, and length of the laminate, respectively. In this derivation it is assumed that the design value of the in-plane loading is equal to the value of loading that the flawed laminate can withstand before failure, which is written as:

$$N_{x(\text{Design})} = N_{x(\text{Flaw})} \quad (1.2)$$

Further, it is assumed that the failure load of the flawed laminate is the ultimate failure load of the unflawed laminate multiplied by some flaw tolerance factor ψ . This relation is written as:

$$N_{x(\text{Design})} = N_{x(\text{Flaw})} = \psi N_{x(\text{Ultimate})} \quad (1.3)$$

As will be discussed later the flaw tolerance factor ψ is a reduction factor ≤ 1 that is assumed to account for various flaw effects such as holes, cracks, or impact damage.

The constitutive relations for plane-stress in an orthotropic medium are:

$$\epsilon_x = \frac{1}{E_x t} N_x - \frac{\nu_{yx}}{E_y t} N_y \quad (1.4)$$

$$\epsilon_y = \frac{1}{E_y t} N_y - \frac{\nu_{xy}}{E_x t} N_x \quad (1.5)$$

$$\gamma_{xy} = \frac{1}{G_{xy} t} N_{xy} \quad (1.6)$$

where

$$\frac{E_x}{\nu_{xy}} = \frac{E_y}{\nu_{yx}} \quad (1.7)$$

In the present paper only a uniaxial loading is considered so that $N_y = N_{xy} = 0$. Thus, from equation (1.4) the ultimate strength of the uniaxially loaded balanced and symmetric laminate is written in terms of the ultimate strain of the laminate as:

$$N_{x(\text{Ultimate})} = E_x t \epsilon_{x(\text{Ultimate})} \quad (1.8)$$

Substituting this into equation (1.3) yields:

$$N_{x(\text{Design})} = \psi E_x t \epsilon_{x(\text{Ultimate})} \quad (1.9)$$

Equation (1.9) can now be solved for the required laminate thickness t , which in turn can be substituted into the laminate weight equation (1.1) to obtain:

$$W = \rho B L \left(\frac{1}{\psi E_x} \right) \frac{N_{x(\text{Design})}}{\epsilon_{x(\text{Ultimate})}} \quad (1.10)$$

A further assumption made in this derivation is that the ultimate failure strain, $\epsilon_{x(\text{Ultimate})}$, is not a function of laminate construction. This assumption should be relatively good for laminates with a large enough percentage of 0° fibers that the failure of the laminate is governed by the

failure strain of the 0° fibers (fiber-dominated failures). However, further exploration of this assumption is beyond the scope of the current paper. With this assumption, and since ρ , B , L , and $N_{x(\text{Design})}$ are all constant for a given design, this equation shows that the minimum weight design for a flawed laminate occurs when the product ψE_x is a maximum. In the next section, a study is made of the variation of this newly proposed merit function ψE_x for one laminate family and one flaw condition.

DESIGN OF A LAMINATE FOR IMPROVED FLAW TOLERANCE IN THE PRESENCE OF A LARGE CIRCULAR HOLE

To demonstrate the application of the merit function ψE_x , the design of a laminate required to carry a specified load in the presence of a large circular hole is considered. The term "large" herein refers to hole diameters large enough that the laminate failure is governed by the stresses due to a stress concentration factor such as described in references 1 and 2. In references 1 and 2, it was shown that for a finite-width graphite/epoxy laminate, failure under uniaxial loading can be closely predicted by using the stress concentration factor when the hole diameter is larger than five inches, independent of hole-diameter to plate-width ratio (see figure 5-b of Reference 2). For this case, the flaw tolerance factor is given by:

$$\psi = \frac{1}{k} \quad (2.1)$$

where k is the stress concentration factor for the laminate. Thus the merit function to be maximized is E_x / k . In the present paper the merit function is demonstrated for the case of an infinite orthotropic sheet with a hole.

Determination of In-Plane Elastic Constants and Stress Concentration Factor For an Orthotropic Sheet

For a balanced laminate, the engineering in-plane orthotropic elastic constants can be determined using

$$E_x = \frac{1}{h} \left(A_{11} - \frac{A_{12}^2}{A_{22}} \right) \quad (3.1)$$

$$E_y = \frac{1}{h} \left(A_{22} - \frac{A_{12}^2}{A_{11}} \right) \quad (3.2)$$

$$G_{xy} = \frac{A_{66}}{h} \quad (3.3)$$

$$v_{xy} = \frac{A_{12}}{A_{22}} \quad (3.4)$$

where

$$\frac{v_{xy}}{E_x} = \frac{v_{yx}}{E_y}$$

In equations (3.1) through (3.4)

$$A_{ij} = \sum_{k=1}^n \bar{Q}_{ij} t_k \quad (3.5)$$

and h = total laminate thickness.

The $\bar{Q}_{ij}$'s for the laminate are the transformed lamina stiffnesses of classical laminate theory and are presented in Appendix A. For an axially loaded infinite orthotropic sheet with a circular hole (see reference 3) the stress concentration factor is written in terms of the engineering elastic constants as

$$k = 1 + \sqrt{2 \left(\sqrt{\frac{E_x}{E_y}} - v_{xy} \right) + \frac{E_x}{G_{xy}}} \quad (3.6)$$

Example Application of New Merit Function

For a baseline laminate, the 48-ply graphite/epoxy laminate presented in reference 2 was chosen. For purposes of determining in-plane orthotropic properties only, the laminate can be considered to be composed of only three layers. These three layers each have thickness t_l and consist of all the 0° plies, all the $\pm 45^\circ$ plies, and all the 90° plies, respectively. The lamina

and laminate material properties for this 48 ply laminate are listed in Table 1 where $\bar{t}_\ell = t_\ell / h$.

Material Properties	Lamina	Laminate
Longitudinal extensional modulus, (psi)	19×10^6	10.2×10^6
Transverse extensional modulus, (psi)	1.89×10^6	5.05×10^6
In-plane shear modulus, (psi)	9.28×10^5	2.93×10^6
Major Poisson's ratio	0.38	0.48

Baseline laminate ply orientation: $(\pm 45 / 0_2 / \pm 45 / 0_2 / \pm 45 / 0 / 90)_{2s}$

$(t_{\text{ply}} = 0.0055", h = 0.264")$

Laminate layer	Layer thickness ratio, $\bar{t}_\ell$
$\bar{t}_0$	0.417
$\bar{t}_{45}$	0.50
$\bar{t}_{90}$	0.083

Table 1: Elastic and Thickness Properties of Example Laminate

By changing the relative values of the $\bar{t}_\ell$'s and varying the angle of the $\pm 45^\circ$ ply to some angle $\pm \theta$, the flaw tolerance of the resulting laminates can be determined using the merit function E_x/k . All calculations were performed using equations (3.1) to (3.4), and equation (3.6) with the stiffness constants given in Appendix A.

In this example, the dimensionless thickness $\bar{t}_{90}$ was left constant at $\bar{t}_{90} = .083$, its value in the baseline laminate. The values of $\bar{t}_0$ and $\bar{t}_\theta$ were then varied from 0 to .917 while holding the sum $\bar{t}_0 + \bar{t}_\theta = 0.917$ a constant, and θ was varied from 20° to 60° . The effect that these changes have on the laminate stiffness E_x and stress concentration factor k is shown in Figures 1 and 2 respectively. As expected, E_x increases nearly linearly for increasing $\bar{t}_0$. The stress concentration factor k , however, increases in a non-linear manner. The merit function, E_x/k , is plotted for the same range of parameters in Figure 3. Also included on each figure is a horizontal line corresponding to the ordinate parameter for an isotropic laminate of the same constituent lamina.

Figure 3 indicates that maximum values of the merit function E_X/k do occur, and that there are values of the merit function greater than that for the baseline laminate. To study the characteristics of the laminates with high values of the merit function, four cases shown as dots and labeled 1 to 4 in the figures are investigated herein. The cases are described as follows

1) For this case, the laminate angle was held constant at 45° , and the thickness $\bar{t}_0$ was increased until the merit function E_X/k became a maximum at a value of $\bar{t}_0 = 0.7$ (see Figure 3). The resulting increase in the merit function is about 10% for this case. However, as shown in Figure 4, the shearing stiffness decreased by 39%, which may not be acceptable for some applications. The corresponding Poisson's ratios for these laminates are given in Figure 5 for sake of completeness in studying the characteristics of the laminates.

2) For this case the thickness $\bar{t}_0$ was held constant and the angle θ was reduced to 25° , resulting in an increase in the merit function of about 12%. Again the shearing stiffness decreased significantly, 28% in this case.

3) & 4) For these cases both $\bar{t}_0$ and θ were changed in such a fashion as to hold the shearing stiffness equal to that of the baseline laminate. For case (3), $\bar{t}_0=0.35$ and $\theta = 35^\circ$, while for case (4), $\bar{t}_0=0.24$ and $\theta = 30^\circ$. For both of these cases the increase in the merit function is about 5%.

These increases in the merit function would represent corresponding decreases in the laminate weight for strength-designed laminates, as indicated by the weight equation (1.10). It should also be pointed out that the achievable increases in the merit function found in this paper are for thickness and angle variations away from nominal for the specific 48 ply laminate selected as an example. These percentage increases will change depending on the initial laminate. Thus, the performance of a flawed laminate using this new merit function should be maximized on a case-by-case basis.

Isotropic Laminate Properties

As a point of reference, the properties for an isotropic laminate are included on each figure. To accomplish this, the effective in-plane properties for an isotropic laminate were calculated using the graphite/epoxy lamina values

listed in Table 1. These resulting isotropic values are $E = 7.73 \times 10^6$ psi, $\nu = 0.318$, and $k = 3$. For this isotropic laminate, the value of the merit function is $E_x/k = 2.6 \times 10^6$ psi. For comparison, the value of the merit function for the baseline case of the previous example was 3.1×10^6 psi. Thus, the baseline orthotropic laminate has a flaw tolerance performance 20% better than an isotropic laminate.

Merit Function Discussion and Implications

Application of the newly proposed merit function ψE_x for flawed laminates was demonstrated using an infinite graphite/epoxy laminate with a circular hole. This laminate was a 48 ply $(\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)_{2s}$ lay-up. Results are also given for a corresponding isotropic laminate. To provide insight into the characteristics of laminates which have improved flaw tolerance, parametric plots in figures 1 - 5 were made of E_x , k , E_x/k , G_{xy} , and ν_{xy} for a general $(0_m, \pm \theta_n, 90_p)$ laminate. From the results of the parametric plots the following trends are observed:

- 1) Although the stress concentration factor k increases with increasing laminate stiffness, the axial stiffness E_x increases faster resulting in a higher value of the merit function E_x/k , (Figures 1, 2 and 3).
- 2) Increases in the merit function tend to be accompanied by reductions in the laminate shearing stiffness G_{xy} (Figure 4).
- 3) Laminates with high values of the merit function also tend to have high values of the major Poisson's ratio ν_{xy} (Figure 5).

The structural implication of these trends can be properly evaluated only in the context of integration of the laminates into a built-up structure for specific applications.

CONCLUDING REMARKS

In the present paper a new and simple merit function is proposed for maximizing the strength performance of flawed composite laminates for different design requirements. An example is also presented of using the

merit function to improve the flaw tolerance performance of a practical graphite/epoxy laminate.

It is well recognized that the flaw tolerance of a laminate can change considerably, depending upon its effective in-plane orthotropic stiffness properties. For example, the stress concentration factor of a $\pm 45^\circ$ laminate is quite low (~ 2) while the stress concentration factor for a unidirectional laminate is quite high (~ 6). A corresponding fact for these laminates is that the extensional stiffness for the $\pm 45^\circ$ laminate is very low, while that for the unidirectional laminate is very high. Between these extreme cases there exist many laminates, each of which has different values of the stress concentration factor and in-plane stiffnesses. A logical question that remains to be answered is, which is best from a flaw tolerance aspect? Although low-stiffness laminates tend to have lower stress concentration factors, they carry less load by virtue of their lower stiffness. Thus, it seems that there could be an optimum laminate which carries the greatest load in the presence of a flaw.

The present paper introduces the concept of a flaw tolerance factor ψ which accounts for the ultimate load reduction caused by a flaw. It is then shown that the minimum weight of a strength-designed laminate in the presence of a flaw will occur when the merit function, ψE_X , is a maximum. Thus, the use of this merit function permits a rational selection of laminate lay-up for maximizing its flaw tolerance.

An example of the use of this merit function is presented for the case where the laminate flaw is a large circular hole. This is the simplest flaw case to study because failure is well predicted by the laminate stress concentration factor. The results of the application of this merit function to other flaw types is beyond the scope of the present paper.

To study the application of this merit function, a practical 48-ply $(\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)_{2s}$ graphite/epoxy laminate was selected from a previous reference. The relative values of the thicknesses of the plies and the angle θ were varied to obtain the maximum value of the merit function ψE_X . The results from this study indicate that an increase of 10% could be obtained for the merit function with a corresponding decrease in laminate weight. It is also noted that this percentage is valid only for the particular laminate studied, and that the merit function would have to be applied on a

case-by-case basis depending upon the specific structural design requirements.

As a further demonstration of the use of the merit function, its value was calculated for an isotropic laminate for comparison with the orthotropic $(\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)_{2s}$ laminate. Results of this study showed that the orthotropic laminate's flaw tolerance merit function was 20% greater than that of the isotropic laminate. Thus, the use of the merit function provides a simple, rational basis for discriminating among candidate laminates for a specific application.

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APPENDIX A: Orthotropic Elastic Constant Expansion

In this expansion, $\bar{t}_l$ is the dimensionless thickness of each of the three layers of the laminate. For an orthotropic lamina the Q_{ij} 's are defined as:

$$Q_{11} = \frac{E_{11}}{1 - \nu_{12}\nu_{21}}$$

$$Q_{22} = \frac{E_{22}}{1 - \nu_{12}\nu_{21}}$$

$$Q_{12} = \frac{\nu_{12}E_{22}}{1 - \nu_{12}\nu_{21}}$$

$$Q_{66} = G_{12}$$

The $\bar{Q}_{ij}$'s for the three-layer laminate considered in this paper are found by using the stiffness transformation equations from reference 4.

For the 0° plies

$$\begin{aligned}\bar{Q}_{11} &= Q_{11} \\ \bar{Q}_{22} &= Q_{22} \\ \bar{Q}_{12} &= Q_{12} \\ \bar{Q}_{66} &= Q_{66}\end{aligned}$$

For the 90° plies

$$\begin{aligned}\bar{Q}_{11} &= Q_{22} \\ \bar{Q}_{22} &= Q_{11} \\ \bar{Q}_{12} &= Q_{12} \\ \bar{Q}_{66} &= Q_{66}\end{aligned}$$

For the $\pm\theta$ plies

$$\begin{aligned}\bar{Q}_{11} &= Q_{11}\cos^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\sin^4\theta, \\ \bar{Q}_{22} &= Q_{11}\sin^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta, \\ \bar{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66})\sin^2\theta\cos^2\theta + Q_{12}(\sin^4\theta + \cos^4\theta) \\ \bar{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + Q_{66}(\sin^4\theta + \cos^4\theta)\end{aligned}$$

Substituting these equations into equation (3.5) and simplifying gives the laminate stiffnesses, A_{ij} , as:

$$\begin{aligned}\frac{A_{11}}{h} &= \frac{E_{11}}{1 - \nu_{12}\nu_{21}} (\bar{t}_0 + \bar{t}_\theta \cos^4 \theta) \\ &+ \frac{E_{22}}{1 - \nu_{12}\nu_{21}} (\bar{t}_{90} + \bar{t}_\theta (2\nu_{12} \sin^2 \theta \cos^2 \theta + \sin^4 \theta)) \\ &+ 4G_{12} \bar{t}_\theta \sin^2 \theta \cos^2 \theta\end{aligned}$$

$$\begin{aligned}\frac{A_{22}}{h} &= \frac{E_{11}}{1 - \nu_{12}\nu_{21}} (\bar{t}_{90} + \bar{t}_\theta \sin^4 \theta) \\ &+ \frac{E_{22}}{1 - \nu_{12}\nu_{21}} (\bar{t}_0 + \bar{t}_\theta (2\nu_{12} \sin^2 \theta \cos^2 \theta + \cos^4 \theta)) \\ &+ 4G_{12} \bar{t}_\theta \sin^2 \theta \cos^2 \theta\end{aligned}$$

$$\begin{aligned}\frac{A_{12}}{h} &= \frac{E_{11}}{1 - \nu_{12}\nu_{21}} (\bar{t}_\theta \sin^2 \theta \cos^2 \theta) \\ &+ \frac{E_{22}}{1 - \nu_{12}\nu_{21}} (\nu_{12}(\bar{t}_0 + \bar{t}_{90}) + \bar{t}_\theta \sin^2 \theta \cos^2 \theta + \nu_{12} \bar{t}_\theta (\sin^4 \theta + \cos^4 \theta)) \\ &- 4G_{12} \bar{t}_\theta \sin^2 \theta \cos^2 \theta\end{aligned}$$

$$\begin{aligned}\frac{A_{66}}{h} &= \frac{E_{11}}{1 - \nu_{12}\nu_{21}} (\bar{t}_\theta \sin^2 \theta \cos^2 \theta) \\ &+ \frac{E_{22}}{1 - \nu_{12}\nu_{21}} (\bar{t}_\theta \sin^2 \theta \cos^2 \theta - 2\nu_{12} \bar{t}_\theta \sin^2 \theta \cos^2 \theta) \\ &+ G_{12} (\bar{t}_0 + \bar{t}_{90} - 2\bar{t}_\theta \sin^2 \theta \cos^2 \theta + \bar{t}_\theta (\sin^4 \theta + \cos^4 \theta))\end{aligned}$$

For an orthotropic lamina, the minor Poisson's ratio ν_{21} can be determined using the reciprocity relation (reference 5).

$$\frac{\nu_{21}}{E_{22}} = \frac{\nu_{12}}{E_{11}}$$

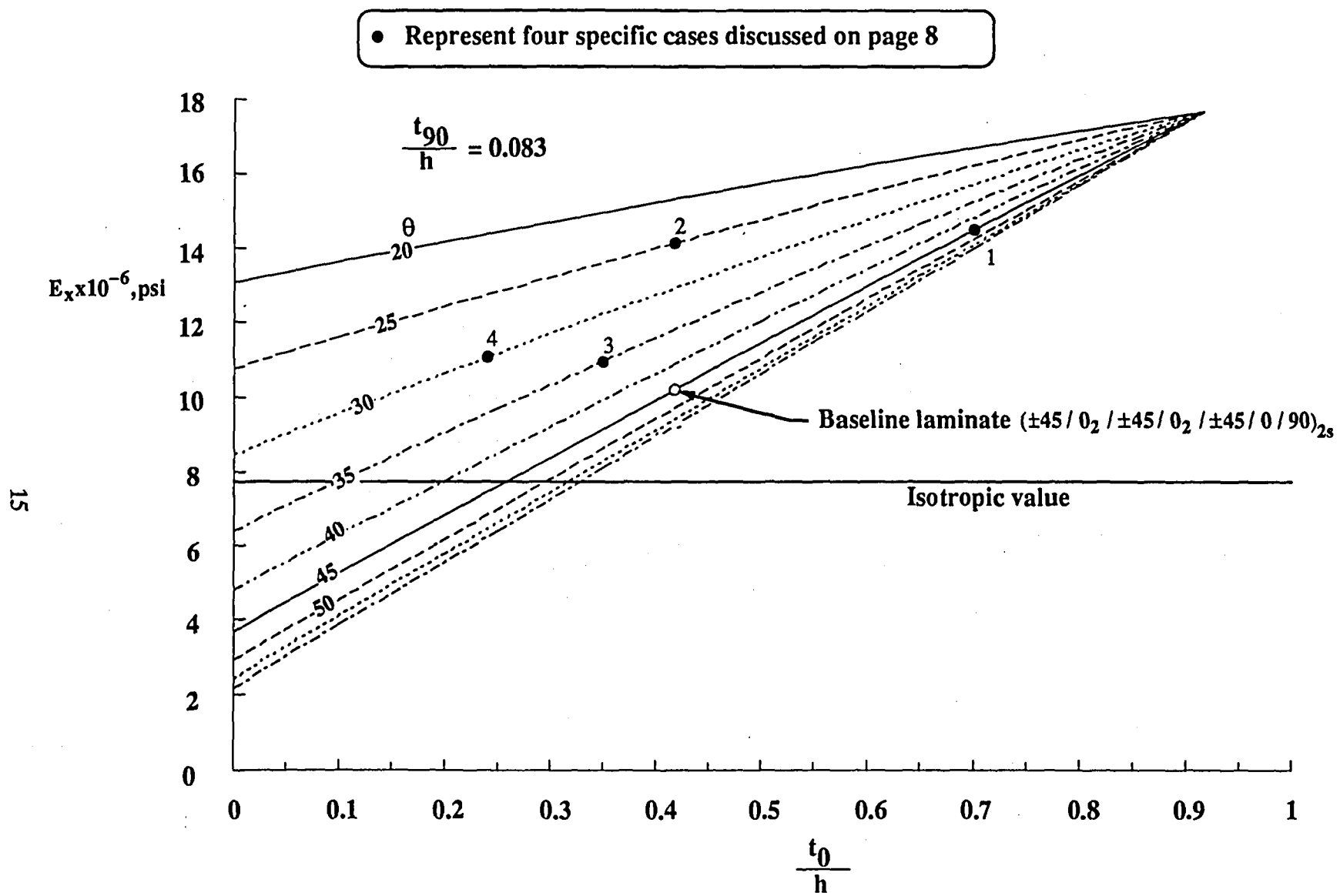


Figure 1 - Extensional modulus for example laminate

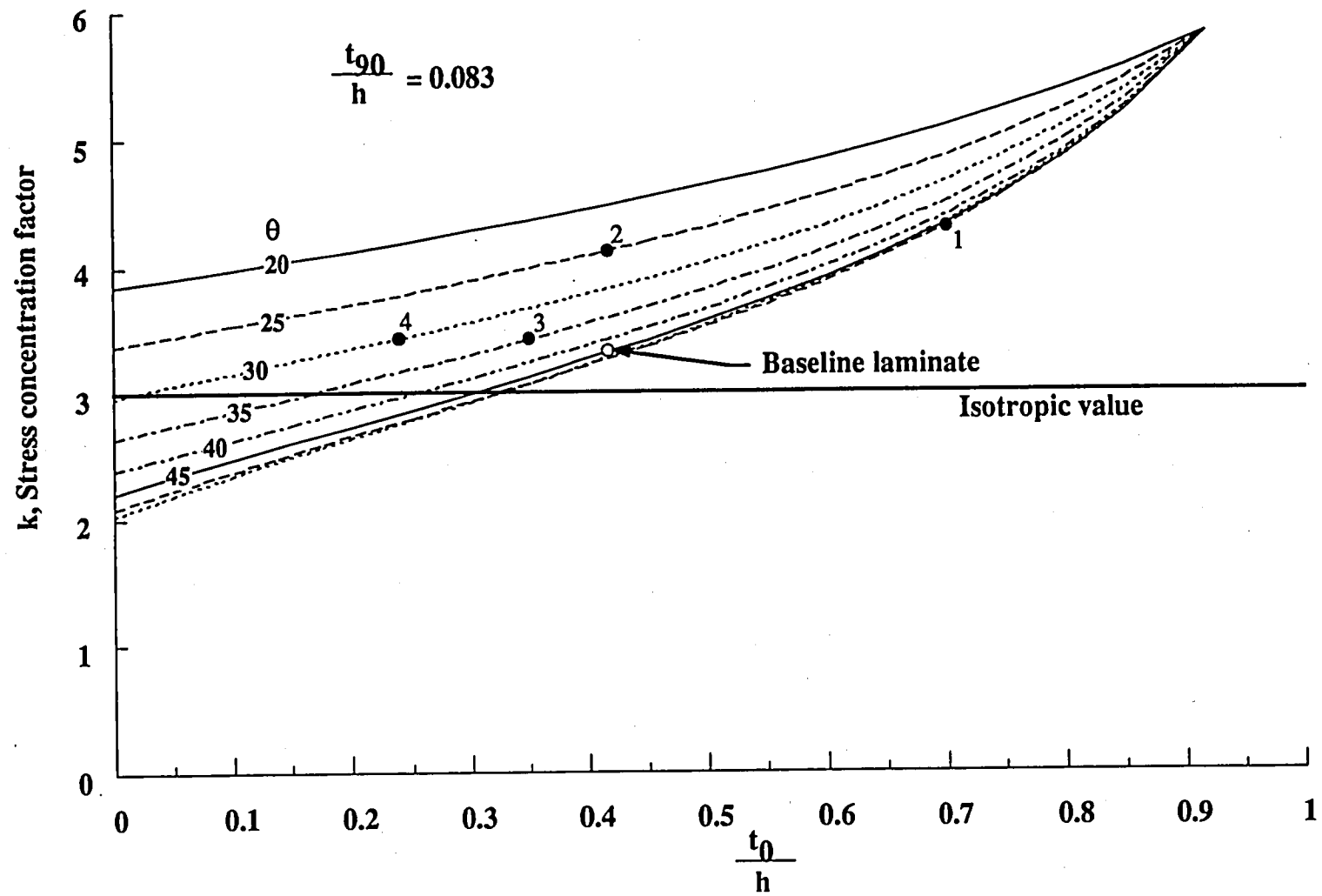


Figure 2 - Stress concentration factor for example laminate.

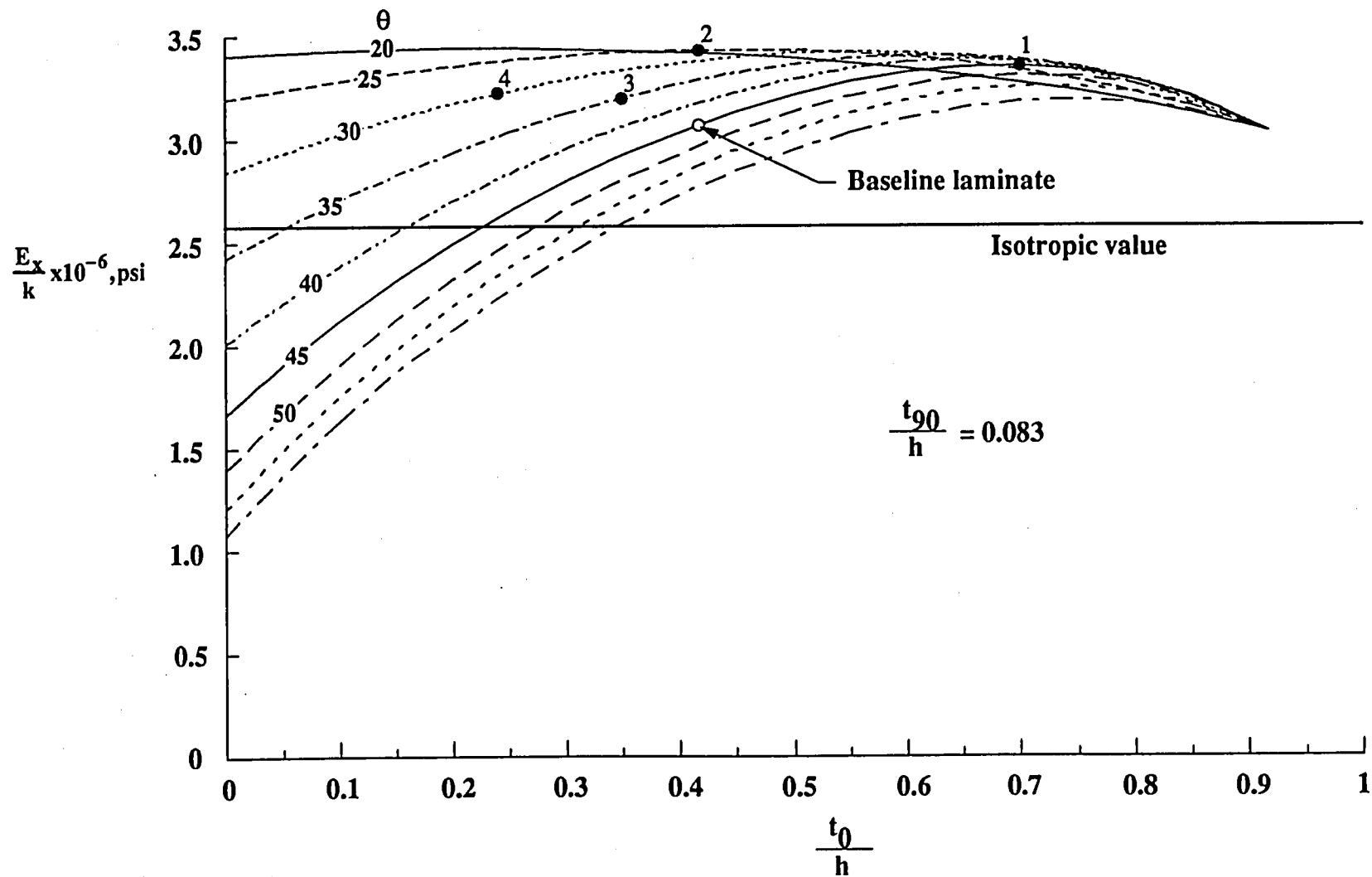


Figure 3 - Merit function for example laminate.

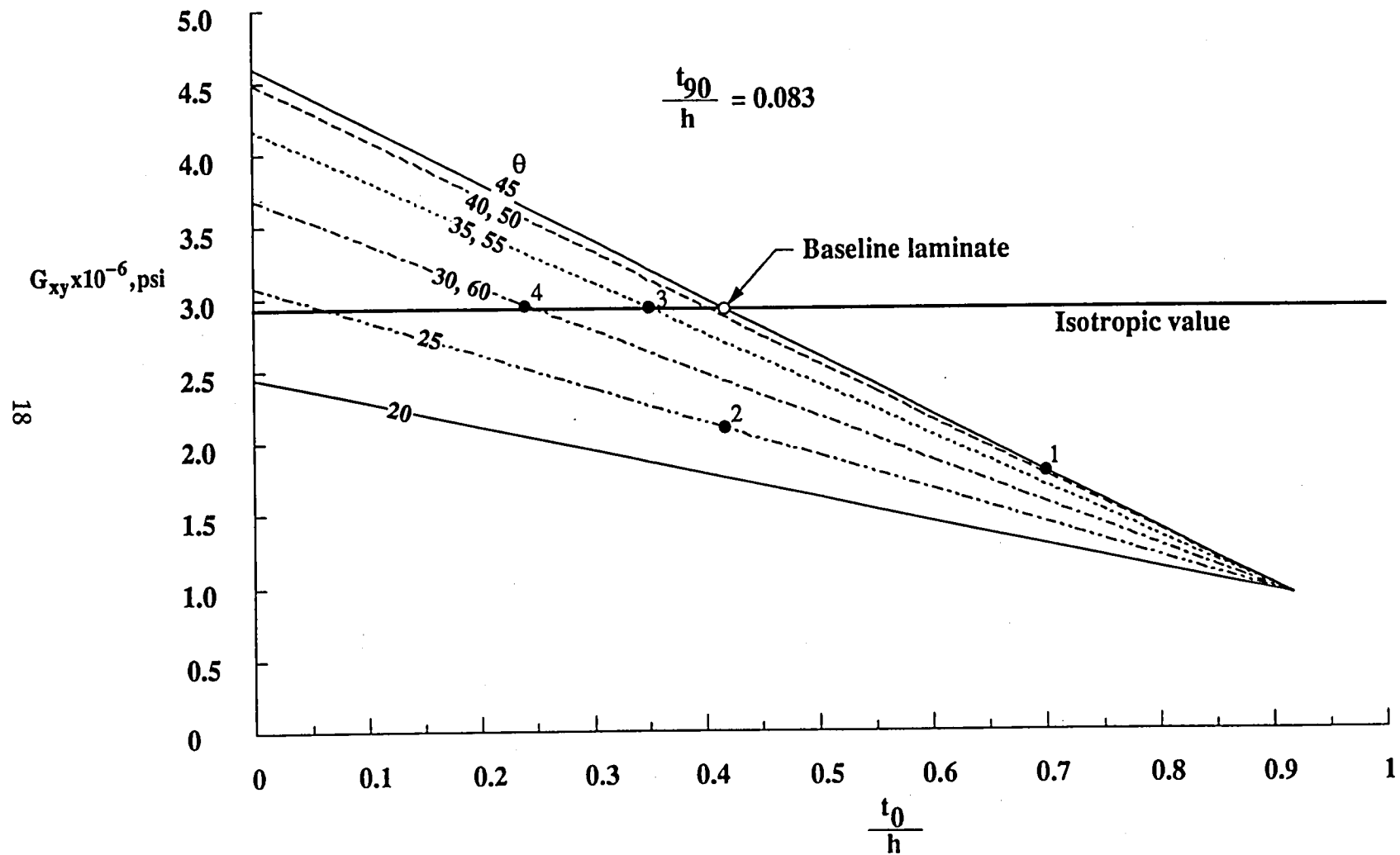


Figure 4 - Shearing modulus for example laminate.

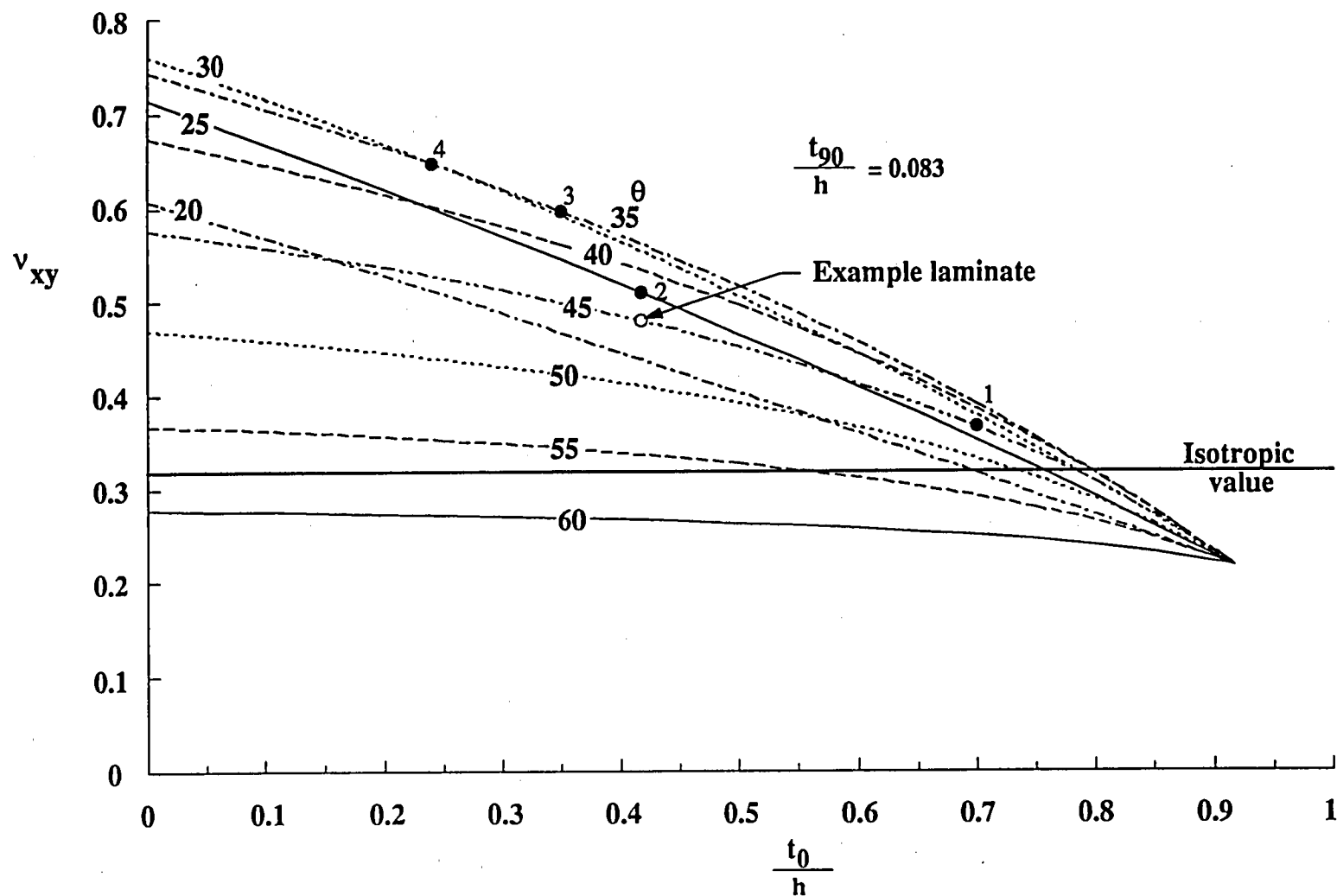


Figure 5 - Major Poisson's ratio for example laminate.

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